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WW Horologii: revised period and X-ray light curve *

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Abstract. We report an improved orbital period of the eclipsing AM Herculis binary WW Hor (=EXO0234.5–5232) which allows to establish the relative phasing of 1983 EXOSAT X-ray and the 1986–89 optical light curves. We find that X-rays and optical cyclotron continuum are produced by the same accreting pole on the magnetic white dwarf. In 1984, WW Hor was not detected with EXOSAT, suggesting that it experienced a low state of accretion.

Key words: cataclysmic variables – AM Herculis binaries – close binaries – stars: individual (WW Hor, EXO0234.5–5232) – X-rays – cyclotron radiation

1. Introduction

WW Hor (=EXO0234.5–5232) was discovered as a new AM Herculis binary by Beuermann *et al.* (1987, paper I) and recognized as an eclipsing system by Bailey *et al.* (1988). The latter authors also found that the orbital period in paper I was incorrect. Looking back at our original data, we found that a cycle count error of one cycle over 10.75 days (= 134 orbits) was responsible for this mistake. The revised spectroscopic orbital period which actually yields a higher χ^2 of the folded radial velocities is $P = 0.0819$ days, consistent with the photometric period reported by Bailey *et al.* (1988). Fig. 1 shows the optical data of paper I folded over the revised period as given by Eq. (1), below.

An important point which remained open in paper I was the relative phasing of the X-ray and optical light curves. The accuracy of our revised period or that of Bailey *et al.* is not sufficient to allow extrapolation back to September 1983 when WW Hor was observed with EXOSAT (paper I). We have, therefore, performed additional CCD photometry through 6 eclipses and derived an improved eclipse ephemeris with the remaining phase error for September 1983 reduced from $\Delta\phi = 0.250$ to 0.002 (90 % confidence error).

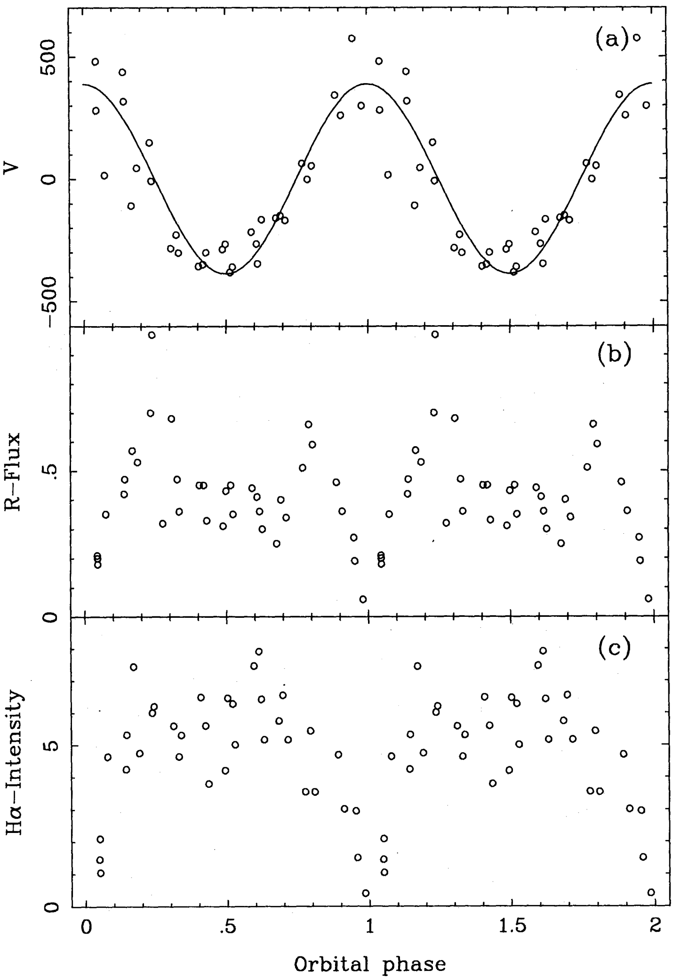

Fig. 1. Optical data of WW Hor taken in October 1986 (paper I) phased on the revised ephemeris of Eq. (1). (a) Radial velocity curve derived from the Balmer emission lines with the best-fit sinusoid, (b) light curve in the 6000 – 7200 Å band in units of 10^{-16} ergs cm^{-2}s^{-1}Å^{-1}, (c) Hα flux in units of 10^{-15} ergs cm^{-2}s^{-1}.

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[*] Based on observations collected with the ESO/MPI 2.2 m telescope in MPI time, the ESO 3.6 m telescope, and with the EXOSAT satellite

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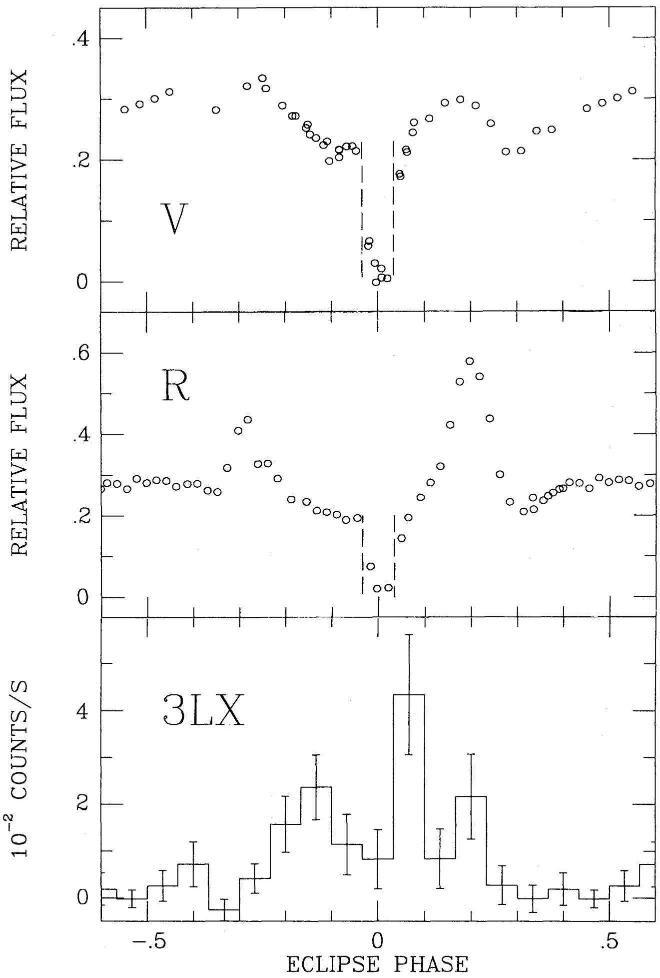

Fig. 2. (a),(b) Light curves of WW Hor in the Bessel R and V bands taken in January 1989. (c) X-ray light curve obtained with the EXOSAT satellite on 6 September 1983, using the low-energy telescope with CMA and 3000 Å Lexan filter. All light curves were folded over the ephemeris given in Eq. (1). Ingress into and egress from eclipse are indicated by the vertical dashed lines.

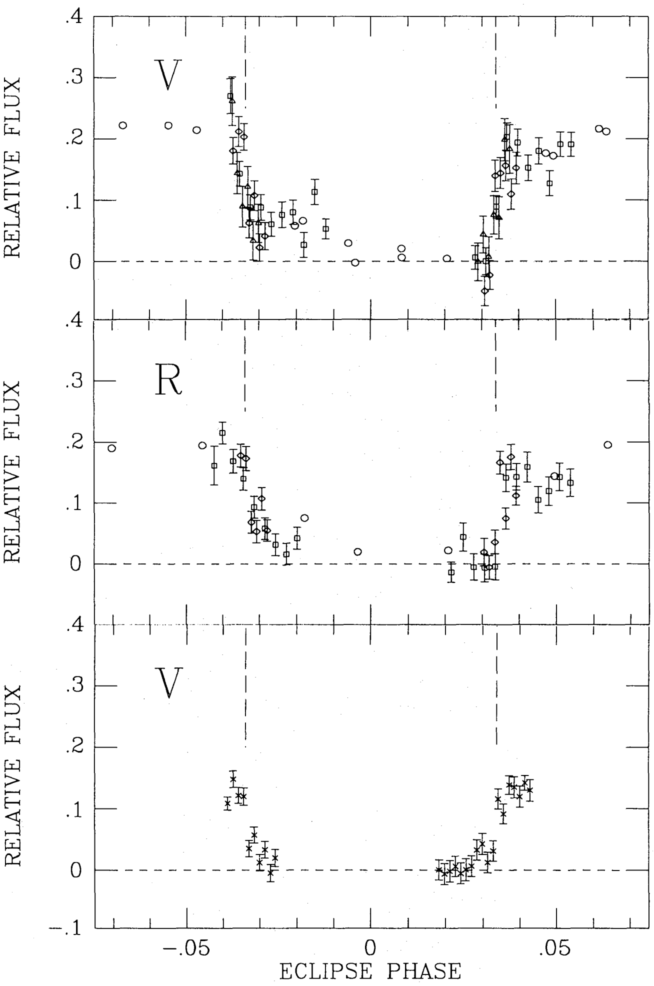

Fig. 3. Photometric results from the stepped images, covering ingress into and egress from eclipse. Time resolution is 10 or 20 sec. Ingress and egress are marked by the vertical dashed lines. *Top and center panels:* V- and R-band data of January 1989 shown along with the data points from the normal exposures (open circles). *Bottom panel:* V-band data of November 1989.

Table 1. CCD photometry and X–ray observations of WW Hor

Date (UT)	UT	Telescope	filter
a) optical			
1989 Jan 21	1:43-2:17	ESO/MPI 2.2 m	Gunn r
Jan 23	1:06-4.01	ESO/MPI 2.2 m	Bessel V
Jan 24	1:39-3:43	ESO/MPI 2.2 m	Bessel R
Jan 25	1:45-2:10	ESO/MPI 2.2 m	Bessel V
1989 Nov 22	3:25-3:38	ESO 3.6 m	Bessel V
b) X-ray			
1983 Sept 6	8:12-11:13	EXOSAT L2	3000 Lexan
1984 Dec 17	10:32-12:00	EXOSAT L1	3000 Lexan

2. Observations

CCD photometry of WW Hor was performed in January and November 1989, using the ESO/MPI 2.2 m and the ESO 3.6 m telescopes at La Silla, Chile, equipped with the Boller and Chivens spectrograph and with EFOSC, respectively. RCA backside illuminated chips with 30μm and 15μm pixel size, respectively, were used as detectors. Full orbital coverage in the V-band and in the R-band was available in January 1989. Stepped images with between 6 and 20 subsequent images on a single CCD frame were taken during ingress into and egress from the individual eclipses. The time resolution for these stepped images was either 10 s or 20 s. Table 1 gives a journal of the observations.

3. Results and discussion

Fig. 2 shows the V-band and R-band light curves obtained in January 1989 (top and center panels). The shapes of these light curves are very similar to those presented by Bailey *et al.* (1988). In particular, the R-band maxima were observed to occur at $\phi = 0.72$ and 0.20 both in our and in the Bailey *et al.* observations. Furthermore, the V-band light curves show a secondary minimum at $\phi = 0.30$ which is also present in the 3400–5300Å band of Bailey *et al.* and, therefore, seems to be a stable feature of the light curves. All magnitudes were measured relative to the somewhat brighter star 1 arc min north of WW Hor and calibrated using standard stars. WW Hor was found at a maximum brightness of $V = 17.55$ and $R = 17.60$, the brightness immediately preceding eclipse ($\phi = 0.95$) was $V = 18.09$ and $R = 18.71$.

Ingress into and egress from eclipse were clearly discernible in the stepped images (Fig. 3). On our time resolution, egress was always sudden. Ingress occurred more or less slowly after an initial sudden drop in brightness. Note that the level of the remnant flux between $\phi = 0.996$ and $\phi \simeq 0$ was variable. The width of the eclipse was measured between the initial drop in brightness and the sudden egress. The average width was 466 ± 4 sec, consistent with the value of 469 s quoted by Bailey *et al.* (1988). The center of the eclipse could be determined on the average to an accuracy of 6 s. The timings for the individual eclipses are listed in Table 2. These timings together with those quoted by Bailey *et al.* allow to derive the improved linear eclipse ephemeris

$$T_o = HJD244\,7126.12782 + 0.080199035E \qquad (1)$$
$$\pm 4 \qquad\qquad \pm 8$$

where the errors refer to the 90 % confidence level. All phases quoted in this paper are based on this ephemeris.

Table 2. Eclipse timings of WW Hor

Cycle	T_o (HJD2440000+)	error of T_o (10^{-5} days)	O–C	Reference
-5128	6714.8668	50	37	(1)
- 176	7112.01283	7	4	(2)
- 175	7112.09307	7	8	(2)
- 174	7112.17318	7	-1	(2)
0	7116.12782	7	-3	(2)
1	7126.20802	7	-13	(2)
76	7132.22295	7	1	(2)
5255	7547.57384	9	9	this work
5280	7549.57870	10	-2	this work
5281	7549.65889	7	-3	this work
5293	7550.62136	5	5	this work
5305	7551.58368	6	-2	this work
9059	7852.65085	5	-3	this work

(1) Beuermann *et al.*, 1987.
(2) Bailey *et al.*, 1988.

From Figs. 2 and 3, it is obvious that in January 1989 the eclipse was total only for $\phi \simeq 0.0$ to $\phi = 0.0338$. The finite variable flux in the phase interval $\phi = 0.9662$ to $\phi \simeq 0.0$ is interpreted as emission from the accretion stream which trails the accretion spot on the white dwarf and disappears behind the secondary later than the spot. The sudden egress refers to the instant when the accretion spot emerges from eclipse.

Fig. 4 illustrates the geometry of the stream as seen by the observer for four selected phases around eclipse. The model calculation is based on an assumed mass ratio $q = M_1/M_2 = 5$ and the system parameters as given by Bailey *et al.* (1988) for this value of q, inclination $i = 83.^{\circ}2$, colatitude of spot $\delta = 24.^{\circ}7$, and azimuth of spot $\psi = 10°$ in phase before eclipse. The primary was taken to have $M_1 = 0.7 M_{\odot}$ and $R_1 = 7.8 \times 10^8$ cm. We make the assumption that, after leaving the inner Lagrangian point, the accretion stream follows the single-particle trajectory until it is stopped by the increasing magnetic-field pressure (see Beuermann *et al.*, 1987). In our model, this occurs at a radial distance from the white dwarf of $r = 20R_1$, after which the stream follows the dipole field lines. The orientation of the magnetic axis was chosen to reproduce the location of the accretion spot on the white dwarf as quoted above (Bailey *et al.*, 1988). The schematic of the resulting light curve in Fig. 4 reproduces the essential features of the observed light curve, the delayed ingress as well as the delayed egress of the stream (compare Fig. 2). Somewhat surprisingly, for these model parameters, the magnetic axis and the spot are located on opposite sides of the line connecting primary and secondary. The magnetic axis points at $\delta_m = 13°, \psi_m = -5°$, the spot is located as given above, and the accreting field line points at $\delta_f = 31°$ and $\psi_f = 13°$.

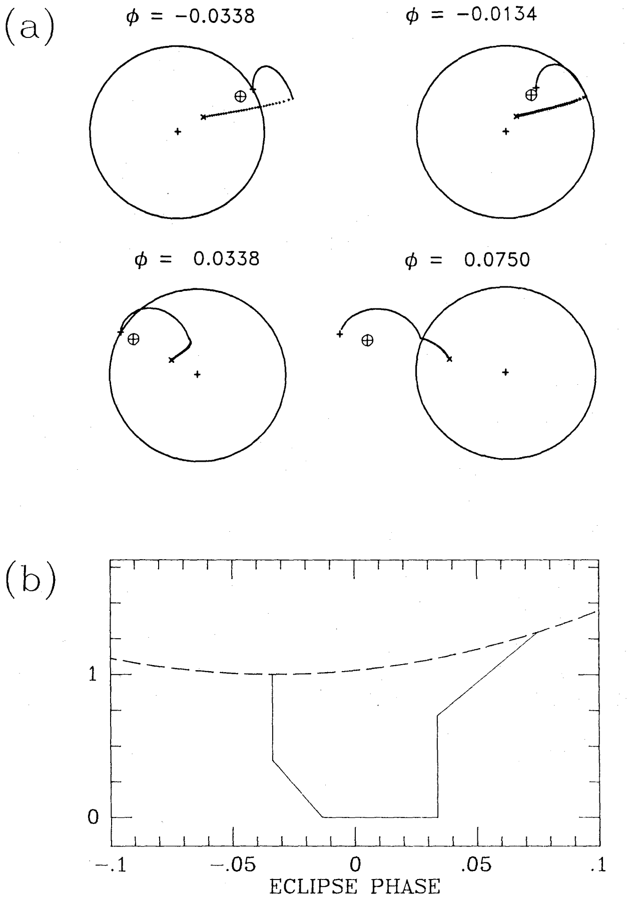

Fig. 4. Aspect of the accretion stream as seen by the observer at four selected orbital phases. Geometric parameters are from Bailey *et al.* (1988) for a mass ratio $M_1/M_2 = 5$ and the model parameters given in the text. The center of the secondary, the L_1 point, the center of gravity, and the center of the white dwarf are indicated by +, ×, ⊕, and +, respectively. A schematic light curve shows the delayed ingress and egress of the stream.

We now turn to the EXOSAT observations of WW Hor previously discussed in paper I. Two observations with the thin Lexan filter were performed on 6 September 1983 and on 17 December 1984 (Table 1). Fig. 2 (lower panel) shows the 1983 observation folded over the ephemeris of Eq. (1). The light curve is displayed in 15 phase bins of 7.7 min duration each, of which one is centered on $\phi = 0$. The nominal phase error of Eq. (1) for the time of the 1983 X-ray obseration corresponds to only 13 s. We find that X-ray bright and optically bright phase intervals coincide and that the X-ray light curve is consistent with showing the X-ray eclipse at the expected phase.

In order to test for a clearer appearance of the eclipse in the X-ray data, we arbitrarily shifted the binning in time. A deep minimum with vanishing flux, flanked by high fluxes in the adjacent bins was, in fact, found for one bin centered 4 min before the expected eclipse time, i.e. at nominal phase $\phi \simeq 0.97$. This timing is inconsistent, however, with the optical ephemeris. A possible explanation is that, in addition to the obscuration of the X-ray source in eclipse, pre-eclipse soft X-ray absorption occurs when the line of sight crosses the accretion stream at $\phi \simeq 0.92$. Alternatively, if the eclipse on 6 September 1983 did occur early, the inconsistency with Eq. (1) would imply that the period decreases on a time scale $\sim 10^6$ a. Because of the poor statistics, we cannot presently distinguish between these possibilities. Better X-ray data and further optical data of this source are clearly needed.

The 1984 X-ray observation covers orbital phases $\phi = -0.04$ to $\phi = 0.73$. The source was not detected this time although half of the expected bright phase was covered. It is very likely that WW Hor experienced a low state of accretion at that time.

4. Conclusion

Our improved orbital ephemeris demonstrates that optical and X-ray bright phases coincide. The data suggest an origin of soft X-ray and optical cyclotron emission from the same accretion region (or pole) on the white dwarf. Our results are consistent with the location of this region above the orbital plane as suggested by Bailey *et al.* (1988).

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